ULTRASONIC MEASUREMENT OF PIPE THICKNESS

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INTRODUCTION

The U.S. Navy requires periodic ultrasonic inspection (UT) of many of its piping systems. The inspections, which measure the wall thickness of the pipes, are performed to prevent failures due to corrosion[1], and to guide decisions regarding component life span/replacement. Often, the inspections are performed with digital thickness gages. These thickness gages perform their best when used on flat, smooth, parallel surfaces, and obviously, shipboard piping systems do not always meet these criteria. Typically, pipe diameters vary from less than one inch to greater than twelve inches. Many pipes have surface corrosion which can cause inaccurate measurements when using digital thickness gages. Additional measurement inaccuracies can result from pipes being in difficult to access locations. A case-in-point and motivation for this work is as follows:

The pipe shown in Fig. 1 was ultrasonically inspected and removed from service based on ultrasonic thickness measurements which indicated wall thinning to thicknesses as little as 0.096-inches (a thickness of 0.096-inches was at or below the absolute minimum for this type of pipe). Once the pipe was removed from service (at great expense), mechanical thickness measurements were made at locations corresponding to the ultrasonic measurements. It was found that the average pipe thickness was 0.202-inches and that the pipe thickness never fell below 0.156-inches. There are many possible reasons why the ultrasonic measurements were incorrect, but the two most likely reasons are: the surface corrosion prevented adequate coupling, and the location of the pipe (in-situ) made it difficult to access.

In addition to thickness gages, the Navy often uses flaw detectors to measure wall thickness. Both types of instruments have particular advantages and disadvantages. The advantages of using a digital thickness gage are: limited amounts of training are

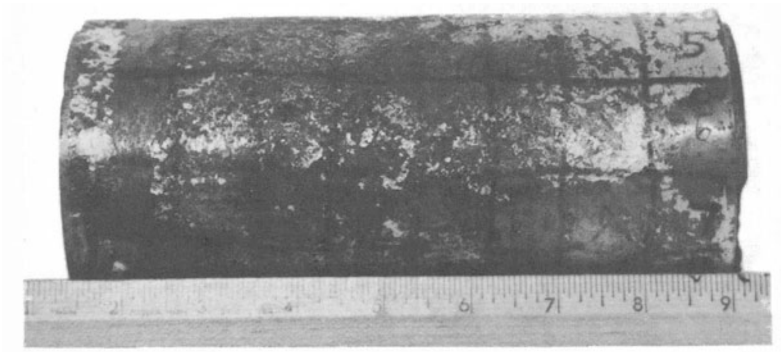

Fig. 1. Photograph of the section of pipe that motivated this work.

required to successfully operate the gages, the gages tend to be small, lightweight, and very portable, and many gages have datalogging capabilities. The disadvantage associated with digital thickness gages is that the waveform cannot be viewed (only a digital readout of thickness is displayed), and so they are only meant to be used where the surfaces are smooth, flat, and parallel - if this criteria is not met erroneous readings may result. The advantages associated with using a flaw detector include: the ability to optimize the inspection system for the particular application and the ability to view the waveform for decision making. The disadvantages of using a flaw detector are: more decisions must be made to perform the inspection, more extensive operator training is required, and the equipment is larger and heavier than digital thickness gages.

No matter what type of instrument is used, ultrasonic thickness measurements are possible due to the fact that the longitudinal wave velocity is essentially constant for a given engineering material. Once the ultrasonic velocity of the material is known, the thickness may be determined by using the following relationship[2]:

$$d = ct \tag{1}$$

where d is the material thickness, c is the velocity of sound in the material, and t is the transit time between the initial pulse and the backwall echo (or between successive backwall echoes). The velocity of sound in the material is determined by measuring the transit time for a known thickness of a similar material (such as a calibration block). If a digital thickness gage is being used, the velocity value is then programmed into the microprocessor so that a direct read-out of material thickness can be made. If a flaw detector is used, the screen width is calibrated to represent a known thickness at the velocity of sound in the material, so that the horizontal scale on the screen may be used to read out thickness.

Since there will always be situations where UT measurements are required to be made on pipes with surface corrosion, using a single instrument which has been shown to be effective for measuring the thickness of pipes with (or without) surface corrosion would benefit the Navy by reducing the extent of personnel training required and the equipment inventory at inspection facilities. Additionally, the instrument should be user friendly (i.e., datalogging capabilities would be nice), and small and lightweight. With this in mind, CDNSWC evaluated a number of types of UT inspection instruments to determine which instrument was the most accurate for measuring the thickness of pipes corroded on the outer diameter (OD).

APPROACH

Eight carbon steel pipes with varying degrees of corrosion on the outer diameter were obtained. Each of these pipes had been removed from actual fleet service and thus represented true Navy problems. The pipes ranged in size from 0.75-inch to 4-inches in diameter and from 0.075-inch to 0.268-inch in thickness. Most of the corrosion appeared to be due to either water trapped beneath lagging or dripping on the pipe. Each pipe was marked with a 1-inch grid system, and each location was given a unique identification. Mechanical thickness measurements were made at each location using either a deep throat micrometer or caliper. The thickness information was input to a spreadsheet and sorted so that locations representing the entire range of available thicknesses could be selected for ultrasonic thickness measurements. One hundred fifty-nine out of the possible 568 locations were selected to represent the various thicknesses of the pipes.

The following five types of instruments were used to measure the thickness at the 159 locations: a pulse-echo (P-E) digital thickness gage with waveform display with a 5 MHz, 0.4-inch diameter, dual element transducer; a digital flaw detector with a 5 MHz, 0.5-inch diameter, single element transducer with a soft wearface; a multiple echo thickness gage with a 5 MHz, 0.5-inch diameter, single element transducer with a soft wearface; a pulse-echo digital thickness gage with a 15 MHz, 0.25-inch diameter, delay line, single element transducer; and a pulse-echo digital thickness gage with a 5 MHz, 0.25-inch diameter, dual element transducer.

All of the ultrasonic measurements were made at the center of the grid location of interest. For the four thickness gages evaluated, the transducer used was the one recommended by the manufacturer for measurements in the thickness range of interest.

DATA ANALYSIS

A mathematical model, relating the mechanically measured thickness of the material to the instrument recorded thickness, was developed for each of the five UT instruments. For this analysis, the mathematical models were assumed to follow a simple linear regression, where the unknown coefficients in the regression equation were calculated from the observed experimental measurements [3]. Specifically, the mathematical model for each instrument was:

$$Y = b_o + b_1 X + \epsilon, \tag{2}$$

where X is the mechanically measured thickness of the pipe,
Y is the experimentally measured thickness using UT,
ϵ is the random error in the model.

The unknown model coefficients, b_o and b_1, were calculated from the observed experimental data using the following equations[3]:

$$b_0 = \frac{1}{n}\sum_{i=1}^{n} Y_i + b_1\frac{1}{n}\sum_{i=1}^{n} X_i \qquad b_1 = \frac{n\sum_{i=1}^{n} X_iY_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i}{n\sum_{i=1}^{n} X_i^2 - (\sum_{i=1}^{n} X_i)^2} \qquad (3)$$

where n = the number of observations.

Following the calculations of the model coefficients, it was necessary to invert the regression equation in order to predict the material thickness based on the observed instrument measurement. Additionally, the derived regression model was used to calculate 95% confidence intervals for the observed experimental measurements[4]. The 95% confidence intervals yield both upper and lower bounds for the true material thickness.

RESULTS AND DISCUSSION

There are many factors which affect the ability of any ultrasonic technique to accurately make thickness measurements; the following discussion describes how a number of these factors may affect thickness measurements.

Calibration: Since material thickness is calculated using a "known" velocity value, any difference between the actual material velocity and the velocity used for instrument calibration will result in a skewing of the ultrasonic thickness measurements. Therefore, ideally, instrument calibration would be performed on a known thickness of a material identical to that being tested. In reality, that is usually not possible. Instead, either the "known" velocity (textbook) for carbon steel or a carbon steel calibration block is used to perform the calibration.

Surface Condition: The surface condition is an important factor to consider when any type of instrumentation is used, but it is particularly important to consider when using a digital thickness gage. Thickness gages are meant to be used where both surfaces are smooth, flat and parallel. If the surface under the transducer is rough, excess couplant can be trapped between the transducer and surface, resulting in erroneous readings. Further, if the backwall is rough, the ultrasonic pulse can be distorted or scattered, resulting in erroneous readings. Additionally, any loose or flaking scale, rust, corrosion or dirt on the surface of the part must be removed as it will interfere with the coupling of the sound energy from the transducer into the material. Lastly, though it is possible to make measurements through thin (a few thousandths of an inch) layers of tightly adhered paint, thick paint will attenuate the signal and may create false echoes [5].

Part Geometry: Curved surfaces of pipes make acquiring accurate measurements more difficult. The center of the transducer must be held steady and perpendicular on the pipe while the measurement is being made. As the transducer gets larger in diameter, the ability to hold the transducer steady and perpendicular to the pipe becomes more difficult.

Couplant: When making measurements in the pulse-echo mode, it is essential that the couplant layer be as thin as possible, otherwise, the thickness of the couplant will be included in the read-out of the material thickness. The following example demonstrates how too much couplant between the transducer and specimen will overestimate a thickness measurement on steel: given the fact that the velocity of sound in a couplant such as glycerin is one-third the velocity of sound in steel [2], a 10 mil thick layer of couplant will be interpreted by the instrument (calibrated to the velocity of steel) to be 30 mils of steel.

Transducer Characteristics: Single element transducers depend on the front and back surfaces of the test piece being parallel. When this condition is met, a wide range of thicknesses can be accurately measured. If the surfaces are not parallel and/or if the surfaces are rough or corroded, a dual element transducer should be used. A dual element transducer has separate crystals for transmitting and receiving mounted on delay lines that are cut at an angle to the horizontal plane. This set-up enables triangulation of the sound energy so that the dual element is not as sensitive to lack of front to back surface parallelism while being more sensitive to echoes from the base of pits that represent minimum remaining wall thickness [5]. A limitation of the dual element is that it has a limited thickness range over which it can operate linearly.

For the work being described here, each of the above factors would have affected the pipe thickness measurements. Although it was not possible to quantify how much error (if any) each factor added to the measurements, it could be concluded from this work that the surface condition of the pipes had the greatest affect on these measurements.

Data Analysis Results

A statistical regression analysis[3] was performed on the collected data (for pipe material ranging from 0.075 inch to 0.268 inch thick) and linear models were developed for each of the five instruments. Possible outlier observations were removed from the data sets before the regression analysis was performed. A summary of the results is shown in Table 1. The root mean square error (MSE), defined as the sample standard deviation of the model error, is a measure of random variability associated with the instrument readings. For example, the pulse-echo digital thickness gage with waveform display had a root MSE of 0.0096 inch, thus for the measurements taken on independent pipes (at the mean pipe thickness used in this experiment) a measurement error [4] of +/- 0.019 inch from the true material thickness will typically be yielded after model correction. On average, the mathematical model derived for this instrument will produce zero error for the calculated or predicted pipe thickness.

Figures 2 through 6 show (a) the data set for each instrument with a one-to-one correlation line plotted through the data, and (b) the experimental instrument readings and the 95% confidence intervals for an individual observation plotted as a function of the true pipe thickness versus instrument measurement. An upper and lower bound for the true material thickness can be determined from the confidence interval plotted in the graphs. For example, if a pipe thickness measurement for a pipe was recorded as 0.140 inch using the multiple echo thickness gage, the lower and upper bound for the true pipe thickness can be determined from Figure 4b by: a) drawing a horizonal line at 0.140 inch which crosses the two confidence lines, b) at the point where the horizontal lines crosses the upper confidence line, drop a vertical line to the horizontal axis, c) at the point where the horizontal line crosses the lower confidence line, drop a second vertical line to the horizontal axis. The upper and lower bounds are defined where the vertical lines intersect the horizontal axis. In this example, the lower bound and upper bound are approximately, 0.117 inch and 0.176 inch, respectively. Alternatively, the upper and lower bounds can be obtained from a look-up table or from equations defined in Draper and Smith [4].

Table 1. Results of statistical regression analysis.

Instrument	Linear Model	Root MSE (inch)	Msmt. Error at Mean Thickness (inch)
P-E Digital Thickness Gage w/ Waveform Display	X = -0.0176 + 1.103 Y	0.0096	+/- 0.019
Digital Flaw Detector	X = 0.0019 + 1.014 Y	0.0105	+/- 0.021
Multiple Echo Thickness Gage	X = -0.0142 + 1.139 Y	0.0130	+/- 0.026
P-E Digital Thickness Gage (Single Element)	X = -0.0372 + 1.239 Y	0.0223	+/- 0.044
P-E Digital Thickness Gage (Dual Element)	X = -0.0187 + 1.181 Y	0.0177	+/- 0.035

where X is the predicted pipe thickness, in., and Y is the instrument measurement, in.

The models derived for each instrument are only valid for the pipe thickness range used in the experimental design, 0.075 inch to 0.268 inch. Extrapolation and application of the confidence intervals outside this material range is possible but not recommended.

Of the five instruments, the pulse-echo thickness gage with waveform display yielded the greatest accuracy for pipe thickness measurements, with a root mean

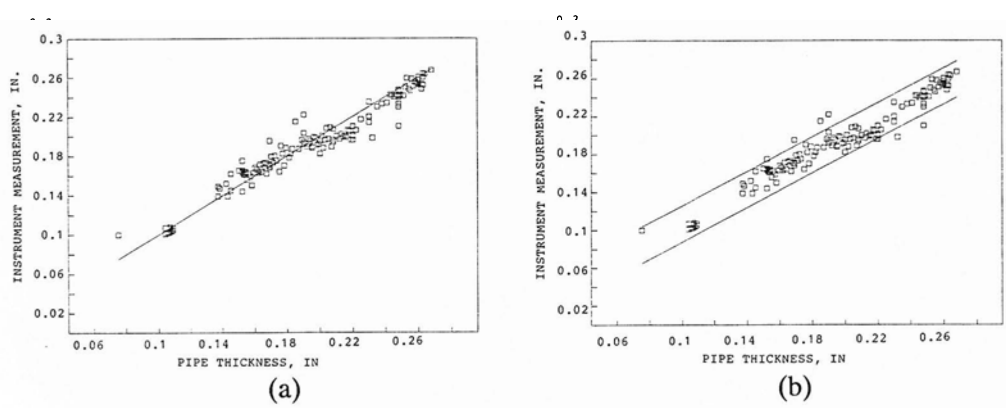

Fig. 2. The data set for the P-E digital thickness gage with waveform display with (a) a one-to-one correlation line, and (b) the 95% confidence intervals.

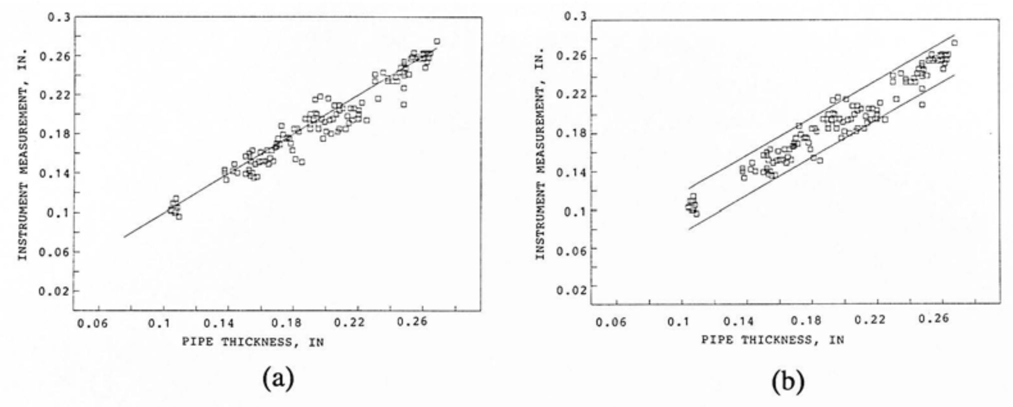

Fig. 3. The data set for the digital flaw detector with (a) a one-to-one correlation line, and (b) the 95% confidence intervals.

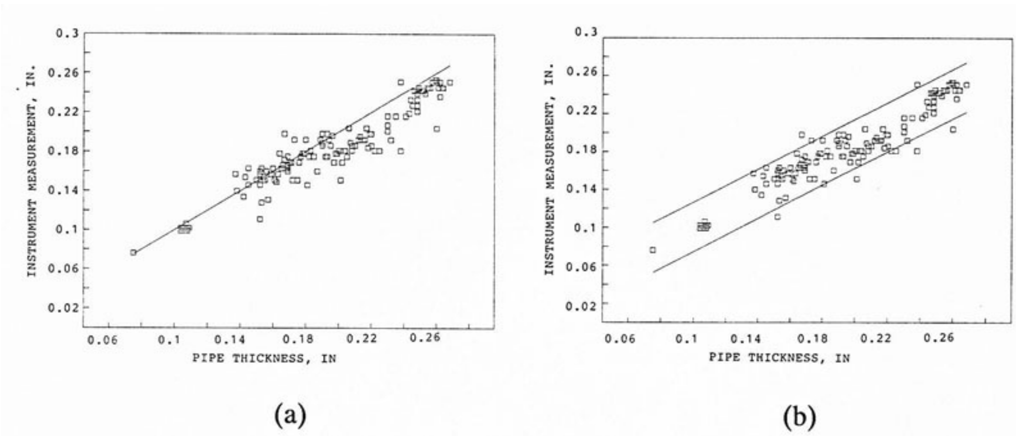

Fig. 4. The data set for the multiple echo thickness gage with (a) a one-to-one correlation line, and (b) the 95% confidence intervals.

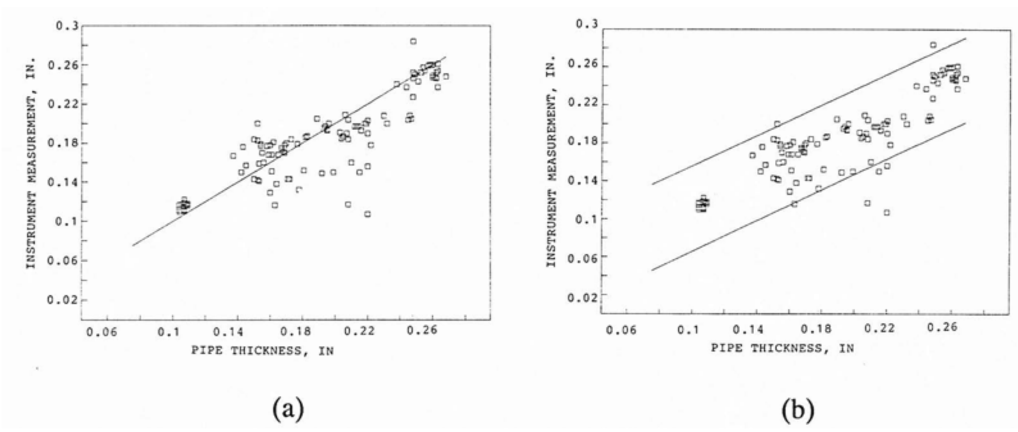

Fig. 5. The data set for the P-E digital thickness gage (single element) with (a) a one-to-one correlation line, and (b) the 95% confidence intervals.

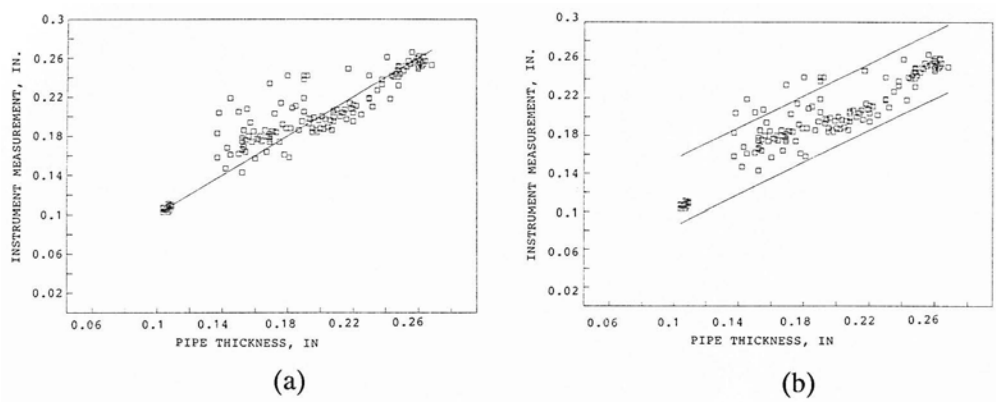

Fig. 6. The data set for the P-E digital thickness gage (dual element) with (a) a one-to-one correlation line, and (b) the 95% confidence intervals.

square error of 0.0096 inch, after model correction. If used in the field by properly trained personnel, it would provide measurements with the accuracy of those made by the digital flaw detector. Additionally, since it is small and lightweight, it would be usable in the very tight spaces that often must be accessed by the field UT operator.

SUMMARY AND CONCLUSION

The objective of this work was to evaluate a number of ultrasonic instruments to determine which was the most accurate for measuring the thickness of pipes with outer diameter corrosion. Five instruments were evaluated, and of the five instruments, the pulse-echo digital thickness gage with waveform display proved to be the most accurate, followed closely by the digital flaw detector. This indicates that the ability to view the waveform is crucial for making accurate thickness measurements on pipes with corroded surfaces. The pulse-echo digital thickness gages without waveform display were the least accurate for making measurements on pipes with OD corrosion and should generally not be used under these conditions.

In conclusion, the pulse-echo digital thickness gage with waveform display evaluated for this study would be an excellent choice to replace the currently used digital thickness gage for performing thickness gaging on Navy piping systems (both with and without OD corrosion). This instrument is small and lightweight like traditional digital thickness gages, but has the advantage that it's accuracy is comparable to that of the digital flaw detector.

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